Journal of Physical Activity and Health, 2016, 13, 94-101
http://dx.doi.org/10.1123/jpah.2014-0468

Human Kinetics
ORIGINAL RESEARCH

Aerobic Fitness and Context Processing in Preadolescent Children

Lauren B. Raine, Mark R. Scudder, Brian J. Saliba, Arthur F. Kramer, and Charles Hillman

***Background*:** There is a growing trend of inactivity among children, which may not only result in poorer physical health but also poorer cognitive health. The purpose of this study was to investigate the relationship between aerobic fitness and proactive and reactive cognitive control using a continuous performance task (CPT). ***Methods*:** Forty-eight 9- to 10-year-old children (n = 24 higher fit [HF] and n = 24 lower fit [LF]) performed an AX-CPT requiring them to respond to target cue-probe pairs (AX) or nontarget pairs (AY, BX, BY) under 2 different trial duration conditions, which modulated working memory demands. ***Results*:** Across trials and conditions, HF children had greater accuracy than LF children. For target trials, the long duration resulted in lower accuracy than the short duration. For nontarget trials, an interaction of duration and trial was observed, indicating that the long duration resulted in decreased BX and BY accuracy relative to the short duration. AY trials had greater accuracy during the long duration compared with the short duration. ***Conclusions*:** These data suggest that fitness may modulate cognitive control strategies during tasks requiring context updating and maintenance, key components of working memory and further support aerobic fitness as a marker of cognitive and brain health in children.

***Keywords*:** cognitive control, updating, maintenance

Physical activity levels of children in the United States have been declining over previous years, and this trend has occurred alongside rising childhood obesity rates such that 33.5% of preadolescent children are now considered overweight or obese.[1,2] A growing literature has revealed that the current sedentary behaviors of children may result in not only poorer physiological health, but also poorer brain health,[3–7] which relates to performance across multiple cognitive and academic domains.[8] Although these relationships are becoming more evident in children, a comprehensive understanding of the specific aspects of cognition that are especially amenable to aerobic fitness during development requires additional study. Previous research suggests that fitness is particularly related to cognitive control, specifically strategic shifts in the control and execution of cognitive functions.[9,10]

Cognitive control refers to the deliberate management of thoughts and actions[11] and describes a group of top-down mental functions that are engaged to select, schedule, and coordinate willed action. The core components of cognitive control include inhibition, cognitive flexibility, and working memory.[12–14] A fundamental feature of working memory is context processing, or the ability to update and actively maintain context/goal information and prepare oneself to respond appropriately to upcoming stimuli.[15] Context information is internally represented and serves to guide attention and inhibitory processes. Examples of context information are goals and prior stimuli or events. Context information also structures the encoding, maintenance, and retrieval of information in memory.[16,17] Context representations are internally represented and held within working memory to guide attention, planning, and behavior for bringing about specific outcomes.[17–20] Thus, superior context maintenance preserves the integrity of relevant information over time within working memory and has important consequences for how information is represented and processed.

More generally, cognitive control has been found to develop across childhood and adolescence,[12,14] a particularly important time as the brain is undergoing maturation. Further, prior research has demonstrated that markers of health behavior such as aerobic fitness relate beneficially to cognitive control during development, with higher aerobically fit children demonstrating superior task performance[5,6,21,22] and a greater capability to flexibly modulate cognitive control processes, relative to their lower fit peers.[9,10] In addition, neuroimaging evidence indicates that as tasks became more difficult, lower fit children have less efficient activation of a network associated with response execution, inhibitory control, task set maintenance, and top-down regulation compared with higher fit children when task performance is held constant across groups.[10]

One explanation for the observed differences between higher and lower fit children may be the processes engaged when completing cognitive control tasks. Braver and colleagues[16] have proposed a theoretical framework based on the differential engagement of control processes. Specifically, the dual mechanism of control (DMC) framework suggests that two qualitatively distinct control processes, proactive and reactive control, are selectively engaged during various context processing tasks.[16] This framework has also provided a means for understanding how brain development throughout the lifespan influences cognitive control.[20,23] Within the DMC framework, proactive control reflects a source of top-down biasing that relies on anticipation and prevention of interference before it occurs. It is involved in the early selection of goal relevant information that is actively maintained in a continuous or anticipatory manner before the occurrence of cognitively demanding events[24,25] and involves the sustained activation of the lateral prefrontal cortex (PFC). The lateral PFC is thought to represent the location for context representation and active maintenance and has been shown to be selectively active in response to the need for maintaining task goals across time.[24–27] Alternatively, reactive control relies on the detection and resolution of interference after stimulus presentation. It is used as a "late correction" mechanism that is mobilized as needed[28] and involves the temporary reinstatement of context information following the onset of a probe stimulus.[25] As such, it has been shown to involve the transient activation of the lateral PFC as a result of either strong bottom-up associations or through the detection of response conflict.[25,29]

Raine (lraine2@illinois.edu), Scudder, Saliba, and Hillman are with the Dept of Kinesiology; Kramer is with the Beckman Institute for Advanced Science and Technology; University of Illinois at Urbana-Champaign.

Only a few studies have examined the influence of fitness on proactive and reactive control strategies. These studies used flanker tasks designed to measure inhibitory control, which limits our understanding of strategic shifts in control, since these tasks were not designed to allow for the explicit examination of different control strategies. As such, there is a need for proper task selection to investigate the relation of various health markers (eg, fitness) to different aspects of cognitive control strategies. One such task that has been used extensively to investigate context processing and strategic shifts in proactive and reactive control is the continuous performance task (AX-CPT). This task consists of a series of letters presented one at a time in cue-probe pairs. There are four types of trial pairs: AX, AY, BX, and BY, and participants are instructed to make a target response to the letter "X" (probe) only when it follows an "A" (cue). Nontarget trials occur when cues are letters other than "A" (collectively referred to as "B") and are followed by probe letters other than "X" (collectively referred to as "Y").

Context representations within working memory are examined using the AX-CPT through performance differences between AY and BX trials. Deficits in the ability to inhibit expectancy bias may be observed in AY trials, and deficits in the ability to inhibit the dominant response may be observed in BX trials. Healthy young adult performance on AY trials is poorer relative to their performance on BX trials, resulting in more false alarms on AY trials because participants accurately process an "A" cue and, based on probability, expect to receive an "X" probe but instead receive a "Y" probe.[15,20,25] Alternatively, they accurately attend to the invalid "B" cues allowing for greater inhibition of the "X" probe on the BX trials.[15,24,25]

Context maintenance within working memory can also be examined using the AX-CPT by manipulating the duration between the cue and probe stimuli. Longer durations require not only proper representation but also active maintenance of the representations.[30] A longer duration between the cue and the probe is considered more challenging because it requires participants to maintain accurate context representations (the correct identity of the presented cue) over a longer interval before responding to the probe, which places a higher demand on context maintenance. A shorter delay between the cue and probe decreases the need to maintain a representation within working memory. With intact context maintenance, the strength of the context representations should remain constant or increase with longer delays. In healthy college-aged populations, AY performance worsens with longer delays, whereas BX performance has been shown to remain constant.[15,20,25] In contrast, older adults show AY performance improvements and longer reaction time in the BX trials condition, suggesting difficulties in updating and representing context.[25]

Accordingly, the current study used an AX-CPT to assess context processing in children who were bifurcated into 2 groups based on their cardiorespiratory fitness levels. The purpose of the study was to assess fitness-related differences in working memory and cognitive control strategies. Specifically, the use of reactive and proactive control strategies was explored in preadolescent children. Context maintenance was further assessed by manipulating the duration between the cue-probe pairs to elevate task demands. Manipulating the duration allowed us to examine both the ability to represent and maintain context information over time. It was hypothesized that all children would perform more poorly on trials containing longer durations between the cue and the probe, but that higher fit children would outperform lower fit children regardless of duration. Further, the greatest differences between fitness groups were expected to be for the most challenging task types (ie, AY and BX).

Methods

Participants

Forty-nine children (27 females) aged 9 to 10 years were recruited for this study. Participants were recruited from the community through flyers, local organizations, and by word of mouth. All participants and their guardians completed written assent and consent, respectively, in accordance with the Institutional Review Board at the University of Illinois Urbana-Champaign. On the day on which laboratory visits occurred, participants were asked to refrain from any structured physical activity, as acute aerobic exercise has previously been found to influence cognition.[31] Fitness and demographic information for all participants is reported in Table 1. Participants qualified for the study if they were either higher fit (HF) (n = 24) or lower fit (LF) (n = 25) as measured by a maximal oxygen consumption ($\text{VO}_{2\text{max}}$) test. HF participants were classified as those scoring above the 70th percentile based on their age and gender norms, and LF participants included those scoring below the 30th percentile based on their age and gender norms.[32] Participants falling between the 30th and 70th percentile were not included in the study.

Aerobic Fitness

Participants completed a $\text{VO}_{2\text{max}}$ test on a motorized treadmill while indirect calorimetry measurements were collected (Parvo Medics True Max 2400; Parvomedics, Inc, Sandy, UT). The test was administered using a modified Balke protocol,[33] and participants ran at a constant speed with incremental grade inclines of 2.5% every 2 minutes until volitional fatigue. Average oxygen uptake (VO_2) and respiratory exchange ratio (RER) were assessed every 20 seconds, and participants wore a polar heart rate (HR) monitor (Model A1; Polar Electro, Finland) throughout the test. Every 2 minutes, ratings of perceived exertion (RPE) were taken using the children's OMNI scale.[34] Relative $\text{VO}_{2\text{max}}$ (mL/kg/min) was evidenced by achieving 2 of the following four criteria: (1) a plateau in oxygen consumption corresponding to an increase of less than 2 mL/kg/min despite an increase in workload, (2) $\text{RER} \geq 1.0$,[35] (3) a peak $\text{HR} \geq 185$ beats per minute (bpm)[33] and a HR plateau,[36] and/or (4) $\text{RPE} \geq 8$.[34]

Table 1 Mean (SE) Demographic Information for HF and LF Groups

Measure	HF	LF
n	24 (14 female)	24 (12 female)
Age (y)	9.9 (0.1)	9.9 (0.6)
Socioeconomic status	2.4 (0.1)	2.1 (0.1)
1	3 (12.5%)	5 (20.8%)
Pubertal timing		
1	16 (66.7%)	10 (41.7%)
1.5	5 (20.8%)	10 (41.7%)
2	3 (12.5%)	4 (16.6%)
K-BIT (IQ)	120.7 (2.2)	116.4 (1.4)
ADHD	35.0 (5.9)	33.3 (4.1)
$\text{VO}_{2\text{max}}$ relative[a]	51.4 (1.0)	37.3 (0.9)
$\text{VO}_{2\text{max}}$ percentile*	82.0 (1.3)	10.5 (1.4)

Abbreviations: ADHD, attention deficit hyperactive disorder; HF, high fit; K-BIT, Kaufman Brief Intelligence Test; LF, low fit; $\text{VO}_{2\text{max}}$, maximal oxygen consumption.

[a] Indicates significant difference, $P < .05$.

Continuous Performance Task

Participants completed the AX-CPT, in which they were instructed to respond as quickly and accurately as possible to a centrally presented sequence of letters presented one at a time as cue-probe pairs. The target letter pair was AX, which was presented amid nontarget letter pairs A"Y", "B"X, and "BY" presented in a random order, with the "B" cue and "Y" probe resembling a host of letters other than A or X. The task was administered using STIM^2 software (Compumedics, Charlotte, NC), and participants were not explicitly made aware of the cue-probe pairings. A capitalized 22-point Arial font was used for all letters, which were presented to each child focally. Participants were instructed to press the left button (both quickly and accurately) every time they saw a letter on the screen, with the exception of when the letter was an X that appeared after the letter A, in which case they were told to press the right button. Each letter was presented for 200 milliseconds and, participants had 1160 milliseconds to respond. Participants completed 2 versions of the task that differed in the duration (short, long) between the cue and probe letters in a pair. In the long version, there was an interstimulus interval (ISI) of 5000 milliseconds between the cue offset and the probe onset, whereas the ISI was 1200 milliseconds in the short version. However, in both versions the time between the probe of one pair and the cue of the following pair was 2000 milliseconds. Before performing the task, participants had the opportunity to practice with randomized ISIs so as not to influence children's expectations. Participants completed 8 total blocks of the task, 4 long duration blocks and 4 short duration blocks, with the same number of trials presented for each version of the task. A within-subjects design was used such that each child completed both the long and short duration conditions in an alternating pattern (eg, long, short, long, etc), which was counterbalanced across higher and lower fit participants. During each block, the AX pairing appeared 70% of the time, with 35 total trials per block. Each of the other three cue-probe pairings (AY, BX, BY) appeared 10% of the time, with 5 trials each per block. Therefore, each condition consisted of 200 pairs of letters (400 letters total). Participants were provided a short break between each block, with the entire session lasting ~45 minutes.

Procedure

Day 1. Following the assent/consent process, the participants' legal guardian completed questionnaires including the Pre-Participation Health Screening,[37] the Attention Deficit Hyperactive Disorder Rating Scale IV (ADHD Rating Scale IV),[38] and a health history and demographics questionnaire. Socioeconomic status (SES) was determined using a trichotomous index based on (1) participation in free or reduced price lunch program at school, (2) the highest level of education obtained by the mother and father, and (3) the number of parents who work full time.[39] SES was confirmed by a second measure, which provided total household income. Together, legal guardians and participants completed the Modified Tanner Staging System[40] to indicate that the participants' pubertal status was at or below a score of 2 at the time of testing. Participants were administered the Kaufman Brief Intelligence Test 2 (K-BIT2)[41] to measure general intelligence. Last, participants completed a VO_2max test to assess their level of aerobic fitness.

Day 2. On the second visit, participants completed the AX-CPT task in a quiet, sound attenuated room. Participants were provided task instructions and given the chance to ask questions both before and after 30 practice trials, which were administered before the start of testing. The outcomes of interest were accuracy and median reaction time (RT) for each trial type (AX, AY, BY, BX). Upon completion of the experiment, participants received $10/h remuneration.

Statistical Analysis

Analyses of nontarget accuracy and median RT were conducted using repeated measures analysis of variance (ANOVA) comparing HF and LF children. Analyses of target trials (AX) were conducted separately because of the differing proportions of target and nontarget trials. Nontarget task performance (median RT, response accuracy) was assessed using separate 2 (Fitness: HF, LF) × 2 (Duration: Long, Short) × 3 (Trial Type: AY, BX, BY) repeated-measures ANOVAs. Family-wise α levels were set at $P = .05$, and post hoc comparisons were conducted using Bonferroni corrected independent- and paired-sample *t* tests. All factors were treated as dependent variables, and analyses with 3 or more within-subject levels used the Greenhouse-Geisser statistic. To control for potential confounding variables, demographic characteristics were *t* tested between groups at $P = .05$.

d′ scores were calculated to provide an index of signal detection, which is an estimate of sensitivity to the difference between targets and nontargets or the ability to correctly discriminate AX from BX trials with regard to the AX-CPT. This score also controls for individual response bias. *d′* is a measure based on the proportion of correct AX trials relative to the proportion of incorrect BX trials, which was computed using BX false alarms or errors of commission. A correction factor was then applied to the *d′* computation in cases of a perfect hit rate or false alarm rate to allow for an unbiased estimation of *d′*. *d′* scores were calculated using the formula: *z*(AX correct trials/AX total trials) – *z*(BX incorrect trials/ BX total trials). Adjustments were implemented for perfect scores, such that if the probability of hits were 1.0 then an adjustment of $2^{-(1/n)}$ (n = number of trials) ($2^{-(1/140)} = 0.9951$) would replace the maximum probability, and if the probability of false alarm rate was 0.0 then the adjustment of $1 - (2^{-(1/n)})$ $(1 - (2^{-(1/n)})$; 0.03401) would replace the minimum probability. Higher values of *d′* indicate increased ability to discriminate between targets and nontargets. This measure of *d′* has been used in previous continuous performance studies,[25,26,42] with lower *d′* scores indicating lower proficiency at using prior context information when attempting to distinguish between targets and nontargets.

Results

Demographic Information

Fitness and demographic information are provided in Table 1. No significant differences were observed for any of the demographic variables between fitness groups. Specifically, HF and LF children did not differ in age, sex, SES, ADHD scores, or K-BIT2 (all $P > .05$). One child (LF) was excluded from analysis due to a K-BIT2 score greater than 3 SDs below the mean, therefore for all analyses 24 HF participants and 24 LF participants were included. Confirming group selection, HF and LF groups differed significantly in their VO_{2max} percentile, with HF children having a greater VO_{2max} percentile (82.0% ± 1.3%) than the LF children (10.5% ± 1.4%).

Continuous Performance Task

Nontarget Trials. The ANOVA for nontarget accuracy revealed 3 main effects: Fitness, $F_{1,46} = 10.0$, $P = .003$, $\eta^2 = 0.18$, with HF participants (74.5% ± 2.1%) having greater accuracy than LF participants (65.1% ± 2.1%) (see Figure 1); Duration, $F_{1,46} = 7.3$, $P = .01$, $\eta^2 = 0.14$, $d = 0.36$, with the short duration (72.0% ± 1.7%) resulting in higher accuracy than the long duration (67.5% ± 1.7%); and Trial, $F_{2,68.8} = 47.0$, $P \leq .005$, $\eta^2 = 0.5$, $d > 0.50$, which indicated that BY (81.8% ± 1.6%) trials had the highest accuracy, followed by AY (67.7% ± 2.1%), and BX (59.8% ± 2.1%) trials.

An interaction of Duration × Trial, $F_{2,92} = 30.0$, $P \leq .005$, $\eta^2 = 0.4$, was also observed (see Figure 2). This interaction was first approached by analyzing each trial separately across the two durations. Post hoc analysis indicated that the long duration resulted in decreased BX (52.1% ± 2.6%) and BY (79.1% ± 1.8%) accuracy relative to the short duration (BX: 67.6% ± 2.5%; BY: 84.6% ± 1.8%), t (47) ≥ 2.9, $P \leq .006$, $d > 0.41$, yet AY trials had significantly greater accuracy during the long duration (71.5% ± 2.4%) compared with short duration (64.0% ± 3.1%), t (47) > 3.1, $P = .003$, $d = 0.40$. Next, the 3 nontarget trial types were compared within each duration. Within the long duration, all trial types were significantly different from one another, t (47) ≥ 3.6, $P \leq .005$, $d > 0.49$, such that the most accurate performance occurred for BY trials (79.1% ± 2.1%), followed by AY (71.5% ± 2.4%) and BX trials (52.1% ± 2.6%). The short condition revealed a similar pattern with the greatest accuracy occurring for BY trials (84.6% ± 1.8%), t (47) ≥ 7.1, $P \leq .005$, $d > 1.13$, however, AY (64.0% ± 3.1%) and BX (67.6% ± 2.5%) trials were not significantly different from one another, t (47) ≥ 1.0, $P = .31$, $d = 0.19$.

The ANOVA for nontarget RT revealed 2 main effects: Duration, $F_{1,46} = 132.8$, $P < .005$, $\eta^2 = 0.74$, $d = 1.0$, with the long duration (659.3 ± 16.1ms) resulting in longer RT compared with the short duration (538.6 ± 19.0 ms) and Trial, $F_{2,\ 57.9} = 55.8$, $P \leq .005$, $\eta^2 = 0.55$, $d > 0.12$, with BX (563.5 ± 24.7 ms) and BY trials (546.8 ± 15.6 ms) having similar RT, and AY (686.6 ± 14.3 ms) trials having the overall longest RT. In addition, there was an interaction of Duration × Trial, $F_{2,92} = 4.6$, $P = .018$, $\eta^2 = 0.09$. This interaction was first approached by analyzing each trial separately across the 2 durations. Post hoc analysis indicated that the long duration (AY: 730.2 ± 15.1 ms; BX: 635.0 ± 25.2 ms; BY: 612.6 ± 15.9 ms) resulted in longer RT relative to the short duration (AY: 643.0 ± 16.2 ms; BX: 491.9 ± 27.6 ms; BY: 481.0 ± 17.0); t (47) ≥ 6.4, $P \leq .005$, $d > 0.78$. Next, the three nontarget trial types were compared within each duration. Within the long duration, AY trials were significantly different from BX and BY trials, t (47) ≥ 4.2, $P \leq .005$, $d > 0.66$, such that the longest RT occurred for AY trials (730.2 ± 15.1 ms), however BX (635.0 ± 25.2 ms) and BY (612.6 ± 15.9 ms) trials did not differ, t (47) ≥ 1.1, $P = .28$, $d = 0.15$. A similar pattern was observed for the short duration, such that the longest RT occurred for AY trials (643.0 ± 16.2 ms), t (47) ≥ 7.7, $P \leq .005$, $d > 0.96$, with BX (491.9 ± 27.6 ms) and BY (481.0 ± 17.0 ms) trials not differing, t (47) ≥ 0.68, $P = .50$, $d = 0.07$. There were no differences in RT between HF and LF participants.

Target Trials. The ANOVA for target trial (AX) accuracy revealed 2 main effects: Fitness, $F_{1,46} = 8.4$, $P = .006$, $\eta^2 = 0.12$, with HF participants (83.0% ± 2.2%) having greater accuracy than LF participants (73.9% ± 2.2%) (see Figure 3); and Duration, $F_{1,46} = 63.6$, $P \leq .005$, $\eta^2 = 0.58$, $d = 0.77$, with the long duration (73.6% ± 1.9%) resulting in lower accuracy than the short duration (83.2% ± 1.4%). The ANOVA for target RT revealed a main effect of Duration, $F_{1,46} = 308.3$, $P \leq .005$, $\eta^2 = 0.87$, $d = 1.22$, with the long duration (587.9 ± 16.6 ms) having a longer RT than the short duration (411.4 ± 18.0 ms). RT analyses did not yield any differences between HF and LF participants.

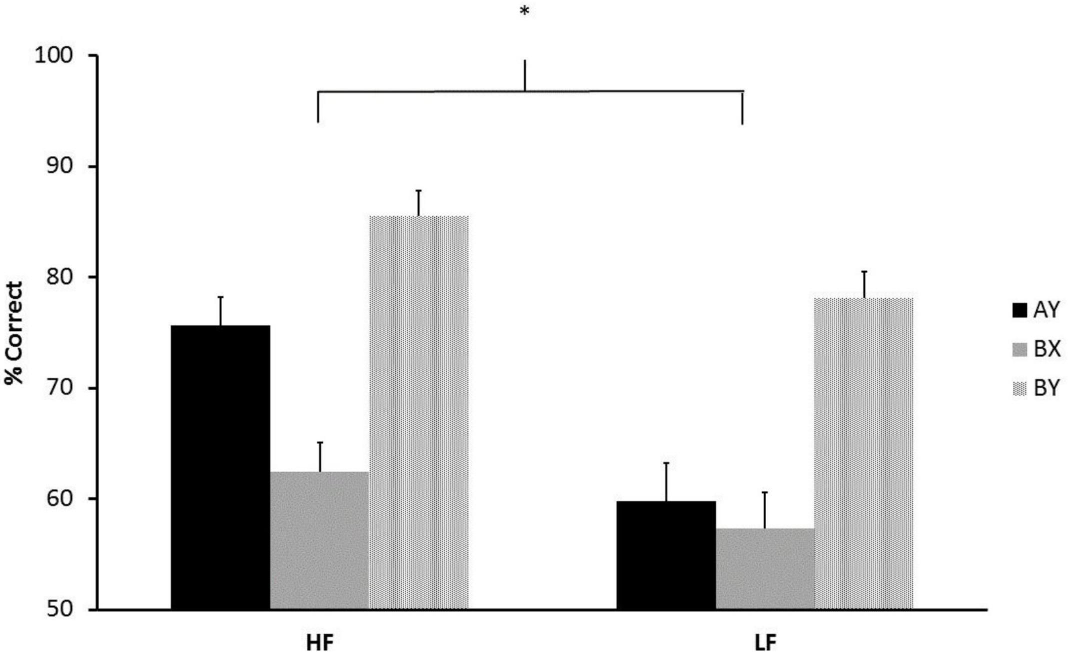

Figure 1 — Response accuracy for higher fit (HF) and lower fit (LF) groups across nontarget trials. HF performance is shown in on the left, and LF is shown on the right. The AY trials are represented by the black bars, BX trials are represented by the gray bars, and BY trials are represented by the checkered bars.

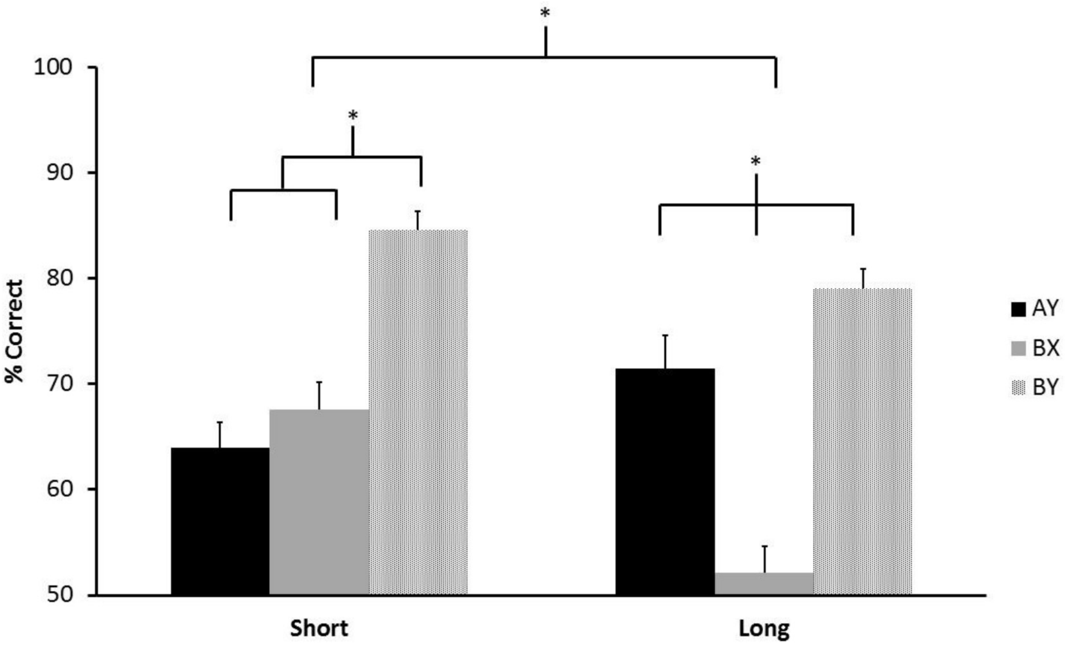

Figure 2 —Response accuracy for short and long delays by nontarget trial types. The short delay is shown on the left, and the long delay is shown on the right. The AY trials are represented by the black bars, BX trials are represented by the gray bars, and BY trials are represented by the checkered bars.

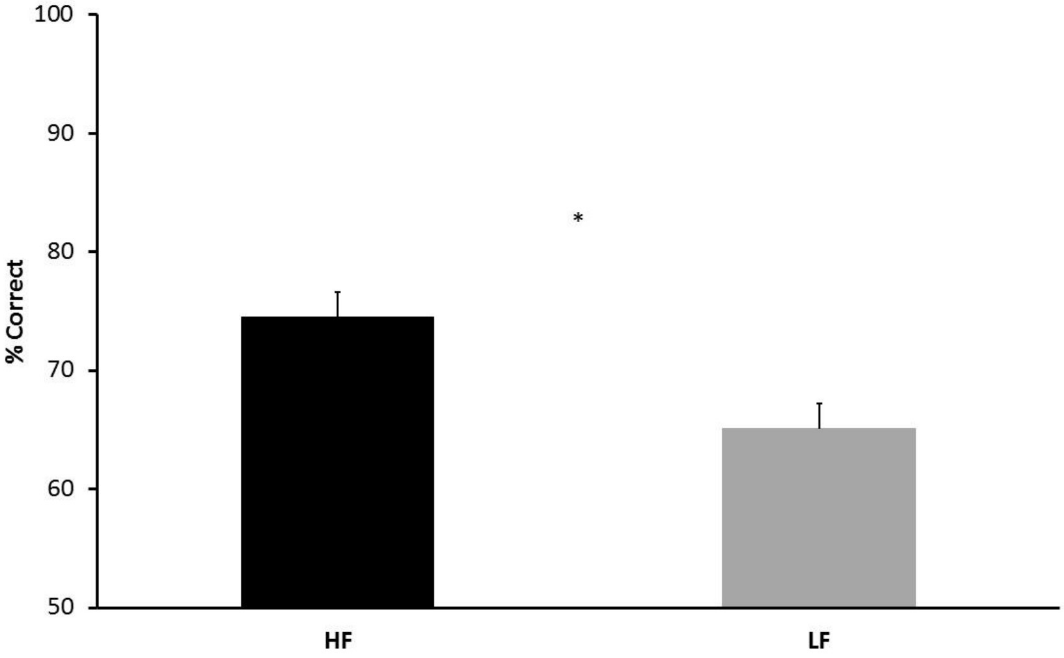

Figure 3 —Response accuracy for higher fit and lower fit groups on target trials. Higher fit (HF) performance is represented with the black bar; lower fit (LF) performance is represented by the gray bar.

The ANOVA for *d′* revealed 2 main effects: Fitness, $F_{1,46} = 9.0$, $P = .04$, $\eta^2 = 0.16$, $d = 0.85$, with HF participants (2.1 ± 0.11) having larger *d′* scores than LF participants (1.6 ± 0.11) (see Figure 4); and Duration, $F_{1,46} = 18.3$, $P \leq .005$, $\eta^2 = 0.29$, $d = 0.67$, with the long duration (1.6 ± 0.1) resulting in smaller *d′* scores than the short condition (2.1 ± 0.1).

Discussion

In this study, we assessed the extent to which aerobic fitness was related to working memory, with a specific focus on the ability to represent and maintain context information in children. The current findings indicated that HF children performed more accurately

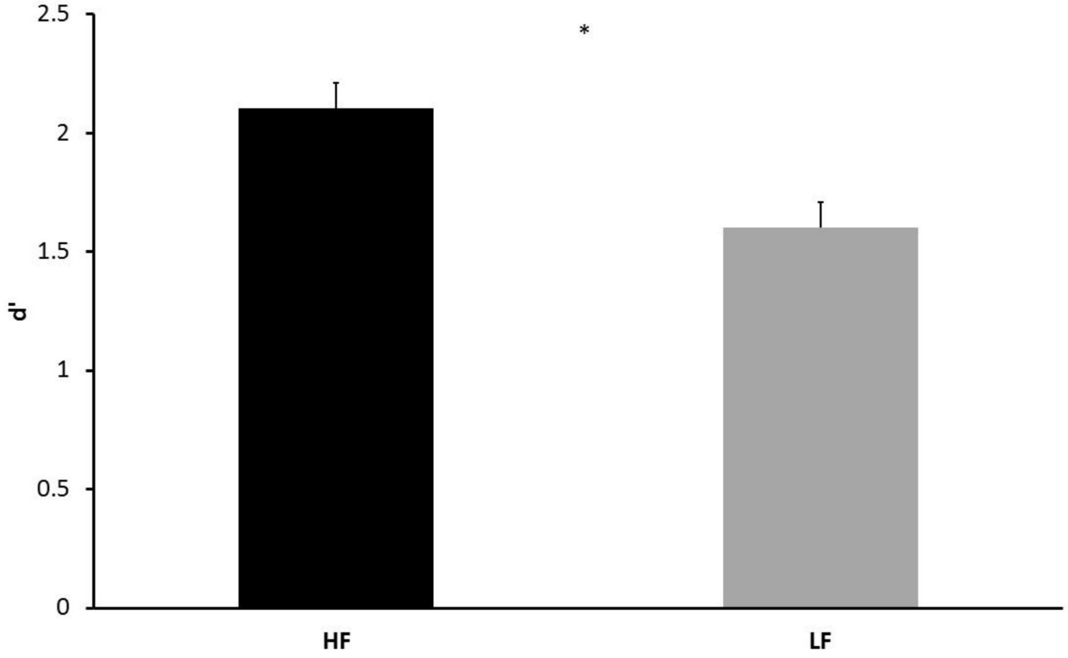

Figure 4 — *d′* for higher fit and lower fit groups. Higher fit (HF) values are represented with the black bar, lower fit (LF) values are represented with the gray bar.

than LF children on both target and nontarget trials of the AX-CPT. Furthermore, HF children were more proficient at using prior context information for distinguishing between targets and nontargets. Overall, children, regardless of fitness level, appeared to use a reactive control strategy when performing the AX-CPT as evinced by decreased accuracy in the BX trials relative to the AY trials, particularly at longer durations.

The current findings extend previous research[9,10] investigating fitness differences in relation to children's cognitive control, with HF children performing more accurately during the AX-CPT than their LF counterparts. Collectively, these findings, along with previous findings in the literature,[9,10] suggest that higher aerobic fitness may relate to better performance on cognitive control tasks involving working memory and inhibition. Specifically, LF children demonstrated more difficulty inhibiting irrelevant aspects of the stimulus environment as well as overriding the prepotent tendency to respond to the frequent trial type, as evidenced by decreased overall accuracy across all trial types and durations. LF children were less efficient at utilizing cue information, leading to a greater number of errors across trial types as evidenced by lower *d´* scores compared with HF children.

These findings corroborate previous work by Pontifex and colleagues,[9] who found that LF children not only have a decreased ability to allocate attentional resources toward task goals, but also experience greater conflict, perhaps due to greater response inhibition. Using Functional Magnetic Resonance Imaging (fMRI), Voss et al[10] extended these findings and found that with increases in task difficulty, lower fit children had greater activation in a neural network associated with cognitive control, with no changes in task performance, reflecting inefficient regulation of cognitive control. In contrast, higher fit children had less activation during the difficult task condition but better performance, suggesting a more efficient activation pattern. Taken together, lower fit children appear to exhibit poorer attentional inhibition during tasks that require the need to inhibit irrelevant aspects of the stimulus environment and display inefficient brain activation to override prepotent response tendencies.

Novel to this investigation was the inclusion of the AX-CPT, which allowed for inquiry into context processing differences in working memory between higher and lower fit children, with particular emphasis placed on strategic shifts in proactive and reactive control. The findings from this study suggest that, in contrast to young adults,[25] children appear to use a reactive control strategy. That is, children have a tendency to react to events as they occur, retrieving information from memory as needed. Since reactive control is a form of late correction, it depends on the recognition and resolution of interference after the event has occurred. Information must be reactivated at the presentation of the probe stimulus, leaving BX trials vulnerable to retrieval-based interference and AY false alarms less likely.[25,28,29] Both higher AY and lower BX performance in the long duration trials are reflective of children's reduced tendency to use either the A or the B stimulus as predictive context for preparing a response to the upcoming probe. This could be reflective of inefficient regulation of cognitive control as the task becomes more difficult. It may also reflect that context information was temporarily encoded but not actively maintained over the delay period. Although this strategy is beneficial for certain task conditions (eg, AY trials), children appear unable to efficiently implement cognitive control strategy during more difficult task conditions (eg, BX trials) as evidenced by decreased accuracy on BX trials in the long duration.

Although the present data suggest that all children use a reactive control strategy on this task, the finding that higher fit children exhibited overall increased accuracy across all trial types and durations suggests that they have superior cognitive control and, therefore, may use cognitive control strategies in a more efficient manner. In addition, lower fit children may be more likely to mistakenly retrieve incorrect information due to retrieval-based interference.

It is important to note that although HF children exhibited overall increased performance relative to LF children, there were no differences in reaction times between groups, suggesting that a speed accuracy tradeoff did not account for group differences.

Manipulations of the delay between the cue and the probe allowed for the investigation of active maintenance of task goals. Long delays result in increased difficulty in maintaining relevant cue information because the information must not only be activated, but also sustained over the delay. Therefore, examination of AY and BX performance under the long delay provides an index of the integrity of context maintenance, as well as working memory ability. When context information is actively maintained, the representation of the "A" cue should stay the same or increase with delay. Therefore, BX accuracy should improve or remain constant with a long delay, and AY accuracy should decrease or remain constant with the long delay when compared with the short delay.[25] This is due to the predictive nature of the A cue, as well as the expectancy bias created by the high frequency of AX trials. However, if goal maintenance is impaired, then BX accuracy will decrease and AY accuracy will increase with longer delays.[18] In the current study, AY accuracy was greater in the long delay than the short delay, suggesting poorer context maintenance. In addition, BX accuracy decreased during the long duration compared with the short duration, further suggesting impaired context maintenance.

This study extends the sparse and highly variable area of research examining control strategies using CPTs in children.[31,43,44] Previous studies have examined different ages as well as manipulated the task design. The stimulus presentation duration in previous studies was longer (500 ms),[31,43,44] as was the response window (2000 ms),[43] and the delays between the cues and probes varied between studies,[31,43,44] with most task designs resulting in a much easier task and thus potentially maximizing performance. The combined effect of presenting the stimuli at a rate that was more than twice as fast and shortening the response window by 50% likely resulted in a more challenging task. These differences in task design and difficulty may have implications for the control strategies engaged. Based on previous studies examining cognitive control in children using a CPT,[43,44] younger children appear to use a more reactive strategy, and as children progress through development, they shift to a more proactive strategy. For example, Chatham et al[43] found that 3.5-year-old children exhibited a reactive control strategy, whereas 8-year-old children exhibited a more proactive strategy in a manner more similar to adults. In a different study, Lorsbach and Reimer[44] found that 6th grade students created stronger representations and were better at maintaining goal information than third grade students who had greater difficulty using the preceding context to overcome the dominant tendency to make a target response.[44] These studies demonstrate the transition from reactive to proactive control may occur during child development such that different periods of rapid brain growth correspond to developmental changes in various executive functions.[44,45] The use of reactive and proactive strategies is also dependent on the task design. Such that the use of specific strategies can be influenced by experimental manipulations (eg, the long and short durations of the task) as well as stable individual and group differences (ie, fitness).

It should be noted that this study is not without limitations. Beyond the previously mentioned differences in task design, this study does not include brain activation or imagining, and thus the present data can only speculate on the relationship between fitness and specific neural networks. Future studies should incorporate these techniques to better understand the cognitive control strategies engaged in and how they might relate to markers of health behaviors. Further, this sample of children is limited to children with above average IQ, and thus these findings may not extend to the entire population of preadolescents. In addition, this study is based on a relatively small sample of children, but power analyses were provided to assist in the strength of the statistical findings. Lastly, this study employed a cross-sectional design, and therefore it is possible that other genetic or lifestyle factors may have contributed to the results.

The results of this study add to the growing literature on cognitive control,[11,12,15,18,25,30,43,44] specifically the context processing strategies used by children during a challenging task. Collectively, these findings extend previous findings in children to suggest that they use a reactive control strategy during a CPT, especially under challenging task demands. In addition, there is a general effect of aerobic fitness on cognitive control during engagement in tasks of this nature. The findings from this study suggest that higher levels of fitness may relate to better inhibitory control and working memory abilities. Thus, aerobic fitness appears to relate to the ability to optimally use cognitive control strategies to enhance task performance. These findings provide further support that greater aerobic fitness may be beneficial for cognitive health and development during preadolescence. Accordingly, these findings highlight the importance of physical fitness for cognitive health and development.

Acknowledgments

Lauren B. Raine was supported by the National Institute for Agriculture under the Illinois Transdisciplinary Obesity Prevention Program grant (2011-67001-30101) to the Division of Nutritional Sciences at the University of Illinois. This grant was funded in part by a grant from the National Institutes of Health (HD069381).

References

1. Ogden CL, Carroll MD, Flegal KM. High body mass index for age among US children and adolescents, 2003-2006. *JAMA*. 2008;299(20):2401–2405. PubMed doi:10.1001/jama.299.20.2401
2. Nadeau KJ, Maahs DM, Daniels SR, Eckel RH. Childhood obesity and cardiovascular disease: links and prevention strategies. *Nat Rev Cardiol*. 2011;8(9):513–525. PubMed doi:10.1038/nrcardio.2011.86
3. Kramer AF, Colcombe SJ, McAuley E, Scalf PE, Erickson KI. Fitness, aging and neurocognitive function. *Neurobiol Aging*. 2005;26:124–127. PubMed doi:10.1016/j.neurobiolaging.2005.09.009
4. Davis CL, Tomporowski PD, McDowell JE, et al. Exercise improves executive function and achievement and alters brain activation in overweight children: a randomized, controlled trial. *Health Psychol*. 2011;30(1):91–98. PubMed doi:10.1037/a0021766
5. Kamijo K, Pontifex MB, O'Leary KC, et al. The effects of an afterschool physical activity program on working memory in preadolescent children. *Dev Sci*. 2011;14(5):1046–1058. PubMed doi:10.1111/j.1467-7687.2011.01054.x
6. Chaddock L, Erickson KI, Prakash RS, et al. A functional MRI investigation of the association between childhood aerobic fitness and neurocognitive control. *Biol Psychol*. 2012;89(1):260–268. PubMed doi:10.1016/j.biopsycho.2011.10.017
7. Castelli DM, Hillman CH, Buck SM, Erwin HE. Physical fitness and academic achievement in third-and fifth-grade students. *J Sport Exerc Psychol*. 2007;29(2):239–252. PubMed
8. Hillman CH, Erickson KI, Kramer AF. Be smart, exercise your heart: exercise effects on brain and cognition. *Nat Rev Neurosci*. 2008;9(1):58–65. PubMed doi:10.1038/nrn2298
9. Pontifex MB, Raine LB, Johnson CR, et al. Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. *J Cogn Neurosci*. 2011;23(6):1332–1345. PubMed doi:10.1162/jocn.2010.21528

10. Voss MW, Chaddock L, Kim JS, et al. Aerobic fitness is associated with greater efficiency of the network underlying cognitive control in preadolescent children. *Neuroscience*. 2011;199:166–176. PubMed doi:10.1016/j.neuroscience.2011.10.009
11. Casey BJ, Tottenham N, Liston C, Durston S. Imaging the developing brain: what have we learned about cognitive development? *Trends Cogn Sci*. 2005;9(3):104–110. PubMed doi:10.1016/j.tics.2005.01.011
12. Diamond A. The early development of executive functions. In: Craik FIM, Bialystok E, eds. *Lifespan Cognition: Mechanisms of Change*. New York, NY: Oxford University Press; 2006:70–95.
13. Blair C, Zelazo PD, Greenberg MT. The measurement of executive function in early childhood. *Dev Neuropsychol*. 2005;28(2):561–571. PubMed doi:10.1207/s15326942dn2802_1
14. Diamond A. Executive functions. *Annu Rev Psychol*. 2013;64:135–168. PubMed doi:10.1146/annurev-psych-113011-143750
15. Braver TS, Barch DM. A theory of cognitive control, aging cognition, and neuromodulation. *Neurosci Biobehav Rev*. 2002;26(7):809–817. PubMed doi:10.1016/S0149-7634(02)00067-2
16. Braver TS, Gray JR, Burgess GC. Explaining the many varieties of working memory variation: dual mechanisms of cognitive control. In: Coway ARA, Jarrold C, Kane MJ, Miyake A, Towse JN, eds. *Variation in Working Memory*. New York, NY: Oxford University Press; 2007:76–106.
17. Barch DM. Disordered cognitive control: a cognitive neuroscience perspective. In: Stuss DR, Knight RT, eds. *Principles of Frontal Lobe Function*. New York, NY: Oxford University Press; 2002:428.
18. Paxton JL, Barch DM, Racine CA, Braver TS. Cognitive control, goal maintenance, and prefrontal function in healthy aging. *Cereb Cortex*. 2008;18(5):1010–1028. PubMed doi:10.1093/cercor/bhm135
19. Casey BJ, Giedd JN, Thomas KM. Structural and functional brain development and its relation to cognitive development. *Biol Psychol*. 2000;54(1-3):241–257. PubMed doi:10.1016/S0301-0511(00)00058-2
20. Braver TS, Cohen JD. On the control of control: the role of dopamine in regulating prefrontal function and working memory. In Monsell S, Driver J, eds. *Control of Cognitive Processes: Attention and Performance XVII.* Cambridge, MA: The MIT Press; 2000: 713–736.
21. Pontifex MB, Scudder MR, Drollette ES, Hillman CH. Fit and vigilant: the relationship between poorer aerobic fitness and failures in sustained attention during preadolescence. *Neuropsychology*. 2012;26(4):407. PubMed doi:10.1037/a0028795
22. Buck SM, Hillman CH, Castelli DM. The relation of aerobic fitness to Stroop Task performance in preadolescent children. *Med Sci Sports Exerc*. 2008;40(1):166–172. PubMed doi:10.1249/mss.0b013e318159b035
23. Braver TS, Barch DM, Cohen JD. Cognition and control in schizophrenia: a computational model of dopamine and prefrontal function. *Biol Psychiatry*. 1999;46(3):312–328. PubMed doi:10.1016/S0006-3223(99)00116-X
24. Braver TS, Barch DM, Keys BA, et al. Context processing in older adults: evidence for a theory relating cognitive control to neurobiology in healthy aging. *J Exp Psychol Gen*. 2001;130(4):746–763. PubMed doi:10.1037/0096-3445.130.4.746
25. Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. *Annu Rev Neurosci*. 2001;24(1):167–202. PubMed doi:10.1146/annurev.neuro.24.1.167
26. Braver TS, Satpute AB, Rush BK, Racine CA, Barch DM. Context processing and context maintenance in healthy aging and early stage dementia of the alzheimer's type. *Psychol Aging*. 2005;20(1):33–46. PubMed doi:10.1037/0882-7974.20.1.33
27. Braver TS, Cohen JD. Dopamine, cognitive control, and schizophrenia: the gating model. *Prog Brain Res*. 1999;121:327–349. PubMed doi:10.1016/S0079-6123(08)63082-4
28. O'Reilly RC, Braver TS, Cohen JD. A biologically based computational model of working memory. In: Miyake A, Shah P, eds. *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*. Cambridge, UK: Cambridge University Press; 1999:375.
29. Jacoby LL, Kelley CM, McElree BD. The role of cognitive control: early selection versus late correction. In: Chaiken S, Trope Y, eds. *Dual Process Theories in Social Psychology.* New York: New Guilford Press; 1999: 383.
30. Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. Conflict monitoring and cognitive control. *Psychol Rev*. 2001;108(3):624. PubMed doi:10.1037/0033-295X.108.3.624
31. Lorsbach TC, Reimer JF. Context processing and cognitive control in children and young adults. *J Genet Psychol*. 2008;169(1):34–50. PubMed doi:10.3200/GNTP.169.1.34-50
32. Hillman CH, Pontifex MB, Raine LB, Castelli DM, Hall EE, Kramer AF. The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. *Neuroscience*. 2009;159(3):1044–1054. PubMed doi:10.1016/j.neuroscience.2009.01.057
33. Shvartz E, Reibold RC. Aerobic fitness norms for males and females aged 6 to 75 years: a review. *Aviat Space Environ Med*. 1990;61(1):3–11. PubMed
34. Armstrong L. *ACSM's Guidelines for Exercise Testing and Prescription*. 8th ed. New York, NY: Lippincott Williams & Wilkins; 2010.
35. Utter AC, Robertson RJ, Nieman DC, Kang J. Children's OMNI scale of perceived exertion: walking/running evaluation. *Med Sci Sports Exerc*. 2002;139–144. PubMed doi:10.1097/00005768-200201000-00021
36. Bar-Or O. *Pediatric Sports Medicine for the Practitioner: From Physiologic Principles to Clinical Applications*. New York, NY: Springer-Verlag; 1983. doi:10.1007/978-1-4612-5593-2
37. Freedson PS, Goodman TL. Measurement of oxygen consumption. In: Rowland TW, ed. *Pediatric Laboratory Exercise Testing: Clinical Guidelines*. Champaign, IL: Human Kinetics; 1993:91–113.
38. Healthy Active Living and Obesity (HALO) Research Group. *Pre-Participation Health Screening for Children*. Ottawa, Canada: Children's Hospital of Eastern Ontario Research Institute; 2010.
39. DuPaul GJ, Power TJ, Anastopoulos AD, Reid R. *ADHD Rating Scale—IV: Checklists, Norms, and Clinical Interpretation*. New York, NY: Guilford Press; 1998.
40. Birnbaum AS, Lytle LA, Murray DM, Story M, Perry CL, Boutelle KN. Survey development for assessing correlates of young adolescents' eating. *Am J Health Behav*. 2002;26(4):284–295. PubMed doi:10.5993/AJHB.26.4.5
41. Taylor SJ, Whincup PH, Hindmarsh PC, Lampe F, Odoki K, Cook D. Performance of a new pubertal self-assessment questionnaire: a preliminary study. *Paediatr Perinat Epidemiol*. 2001;15(1):88–94. PubMed doi:10.1046/j.1365-3016.2001.00317.x
42. Kaufman AS, Kaufman NL. *Kaufman Brief Intelligence Test*. 2nd ed manual. Bloomington, MN: NCS Pearson; 2004.
43. Chatham CH, Frank MJ, Munakata Y. Pupillometric and behavioral markers of a developmental shift in the temporal dynamics of cognitive control. *Proc Natl Acad Sci USA*. 2009;106(14):5529–5533. PubMed doi:10.1073/pnas.0810002106
44. Lorsbach TC, Reimer JF. Developmental differences in cognitive control: goal representation and maintenance during a continuous performance task. *J Cogn Dev*. 2010;11(2):185–216. doi:10.1080/15248371003699936
45. Anderson V. Assessing executive functions in children: biological, psychological, and developmental considerations. *Neuropsychol Rehabil*. 1998;8(3):319–349. doi:10.1080/713755568